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Artificial Intelligence-Based Automated Testing of Augmented Reality and Virtual Reality Applications

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Abstract: *Augmented Reality and Virtual Reality applications have developed rapidly across education, healthcare, gaming, engineering, manufacturing, tourism, training, and other domains. However, testing these applications is considerably more complex than testing conventional two-dimensional software because AR and VR systems combine graphical interfaces, three-dimensional environments, spatial interactions, sensors, tracking systems, motion, audio-visual components, and human interaction. Traditional testing approaches often have difficulty generating realistic test inputs, exploring large numbers of possible interaction states, and identifying visual, spatial, collision, usability, and performance-related faults.*

Artificial Intelligence and Machine Learning provide promising mechanisms for addressing these challenges through automated test generation, intelligent exploration, visual defect detection, reinforcement-learning-based interaction, anomaly detection, predictive analysis, and automated test-result evaluation. Recent research shows that machine-learning-based testing has become one of the prominent techniques in Extended Reality testing, while agent-based and reinforcement-learning approaches can automate exploration and interaction.

Keywords: Artificial Intelligence, Machine Learning, Automated Testing, Augmented Reality, Virtual Reality, Extended Reality

I. INTRODUCTION

Augmented Reality and Virtual Reality represent important components of Extended Reality, enabling users to interact with digital objects, virtual environments, and real-world surroundings in increasingly immersive ways. AR generally combines computer-generated information with the physical environment, whereas VR provides an entirely or predominantly computer-generated environment. The development of these technologies has created new software-engineering requirements because applications must correctly manage three-dimensional scenes, spatial positioning, object interaction, user movement, sensors, rendering, tracking, and real-time responses.

Consequently, testing AR and VR applications cannot rely exclusively on conventional unit, integration, and graphical-user-interface testing. A recent systematic mapping study of XR software testing emphasized that six-degree-of-freedom interaction and other XR characteristics create testing challenges that differ substantially from traditional 2D applications. AI-based automated testing has emerged as a promising solution because AI can learn interaction patterns, identify abnormal behavior, generate test cases, navigate virtual environments, analyze rendered images, and prioritize high-risk test scenarios. Earlier research proposed combining virtual reality, artificial neural networks, and AI with automated software testing, demonstrating the conceptual potential of intelligent test generation and automated error identification.

More recent approaches have moved from conceptual integration toward agent-based, machine-learning, reinforcement-learning, and metamorphic-testing techniques. Therefore, AI-based testing represents an important research direction for improving the reliability, efficiency, scalability, and coverage of AR and VR applications.

NEED FOR AUTOMATED TESTING IN AR AND VR APPLICATIONS

The complexity of AR and VR applications creates a strong need for automated testing. In conventional software, a tester can generally reproduce an input sequence through a keyboard, mouse, touchscreen, or API. In immersive applications, however, user behavior may involve head movement, hand movement, controller gestures, object grabbing, walking, looking around, physical positioning, and interaction with objects distributed throughout a three-dimensional environment.

The same application may behave differently under different device configurations, lighting conditions, tracking accuracy, field of view, frame rates, and physical environments. AR applications additionally depend on camera input, surface detection, environmental understanding, and spatial mapping. Automated testing is therefore required to explore combinations of environmental and interaction conditions that would be impractical to test manually. AI strengthens this automation by enabling systems to learn from previous executions and intelligently select new test actions.

The 2025 XR testing mapping study found machine-learning-based testing to be among the most frequently used specialized testing techniques, particularly because ML can process rich graphical interfaces and detect faults through screenshots and other visual information. AI can consequently reduce repetitive human effort while increasing the breadth of test exploration.

AI TECHNIQUES FOR AUTOMATED AR/VR TESTING

Several AI techniques can be integrated into automated AR and VR testing. Machine Learning can classify application states, detect abnormal behavior, predict failure-prone components, and prioritize test cases. Deep Learning and Computer Vision can analyze screenshots, rendered scenes, object positions, textures, lighting, and visual inconsistencies. Reinforcement Learning is particularly suitable for interactive environments because an intelligent agent can learn which actions lead to new states or potentially faulty conditions. Agent-based testing can combine navigation, reasoning, learning, and decision-making to autonomously explore an interactive XR environment.

The iv4XR framework, for example, was proposed as an agent-based architecture for automated testing of XR systems, with agents designed to support AI capabilities such as reasoning, navigation, and learning. Metamorphic Testing provides another important mechanism when it is difficult to define exact expected outputs. Instead of checking a single expected result, the system evaluates whether known relationships between multiple executions remain valid. Recent research combined metamorphic testing, intelligent agents, and machine learning for automated VR testing, particularly targeting collision and camera-related faults. Together, these approaches provide a foundation for intelligent and scalable testing of immersive applications.

AI-BASED TEST CASE GENERATION

One of the most important applications of AI in AR/VR testing is automatic test-case generation. Conventional manual test design requires testers to anticipate possible user actions and environmental conditions. In a VR environment containing numerous objects and possible movement paths, the number of potential interaction sequences can become extremely large. AI agents can automatically explore scenes and generate action sequences based on previously observed states. Reinforcement learning can reward agents for reaching previously unexplored areas, triggering interactions, or discovering abnormal application behavior.

Deep learning can also identify frequently occurring patterns and generate test cases around unusual or high-risk states. In AR applications, AI-generated tests may vary device orientation, camera position, lighting conditions, surface characteristics, object placement, and user movement. This approach can increase test coverage and reduce dependence on manually scripted scenarios. Research combining deep reinforcement learning and metamorphic testing demonstrated the practical potential of intelligent automated exploration in VR applications, reporting results between 69% and 93% depending on application complexity in an experimental evaluation involving four VR applications. Such findings indicate that AI-generated test cases can provide meaningful automated exploration, although their effectiveness remains dependent on the quality of training environments, reward mechanisms, and application characteristics.

COMPUTER VISION FOR VISUAL TESTING

Computer Vision is especially important for AR and VR because visual correctness is a central component of user experience. Conventional functional tests may verify whether an application performs an operation correctly but fail to detect visual defects such as incorrect object placement, distorted textures, inconsistent lighting, missing objects, incorrect perspective, rendering artifacts, or stereoscopic inconsistencies. AI-based visual testing can compare expected and observed scenes using image-processing and deep-learning techniques.

In AR, computer vision can evaluate whether virtual objects are correctly aligned with physical surfaces and whether tracking errors cause inappropriate placement. In VR, visual analysis can identify scene-rendering errors, object disappearance, camera problems, and other graphical abnormalities. The systematic mapping literature identifies machine-learning-based testing as particularly suitable for rich graphical XR interfaces, including fault identification from application screenshots. Computer-vision-based testing can therefore complement traditional functional testing by providing automated assessment of the visual layer of immersive applications.

AUTOMATED TESTING OF USER INTERACTION

User interaction testing is another major challenge in AR and VR. Interaction may involve controllers, hand gestures, gaze, head orientation, body movement, voice commands, or physical movement. An application may function correctly when a tester follows an expected sequence but fail under slightly different movement trajectories or interaction timing. AI agents can imitate users and explore alternative interaction patterns. Recent work on automated VR testing has specifically addressed the challenge of synthesizing realistic three-dimensional user inputs, such as grabbing objects and using controller triggers.

This represents an important development because realistic user-input generation is necessary for meaningful automated testing. AI-based interaction testing can also be used to investigate usability problems, unreachable objects, incorrect collision responses, interaction dead ends, and inconsistent application states.

PERFORMANCE, USABILITY AND SAFETY TESTING

AR and VR applications must satisfy not only functional requirements but also performance, usability, and safety requirements. Low frame rates, excessive latency, tracking instability, visual inconsistencies, or inappropriate motion can substantially reduce user experience and may contribute to discomfort or cybersickness. AI can analyze performance logs and identify patterns associated with application degradation. Machine-learning models can predict performance failures by examining frame rate, rendering time, memory consumption, device temperature, network conditions, and interaction complexity.

AI can also classify usability problems from user behavior and interaction traces. Automated testing frameworks can monitor whether users become trapped in particular scenes, whether important objects are difficult to locate, and whether interaction sequences are unnecessarily complex. This multidimensional testing is particularly important because XR quality is not determined solely by whether a software function produces the correct output; the application must also maintain stable and believable interaction with the user and environment.

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Comparative Overview of AI-Based AR/VR Testing Approaches

AI-Based Approach	Main Testing Function	AR Application	VR Application	Major Advantage	Major Limitation
Machine Learning	Fault classification and prediction	High	High	Learns patterns from test data	Requires suitable training data
Deep Learning	Visual and scene analysis	Very High	High	Effective for complex visual information	Computationally demanding
Computer Vision	Object and rendering validation	Very High	High	Detects visual/spatial defects	Sensitive to environmental variation
Reinforcement Learning	Autonomous exploration	High	Very High	Learns interaction strategies	Training may be time-consuming
Agent-Based Testing	Intelligent navigation and interaction	High	Very High	Supports autonomous decision-making	Agent design can be complex
Metamorphic Testing	Detection without exact expected output	Medium	High	Useful for complex interactive behavior	Requires suitable metamorphic relations
Anomaly Detection	Runtime fault identification	High	High	Detects unexpected behavior	False positives may occur
Predictive Analytics	Failure and performance prediction	High	High	Supports risk-based testing	Dependent on historical data
AI Visual Testing	Rendering and interface validation	Very High	Very High	Automates visual comparison	Difficult with dynamic scenes
Hybrid AI Testing	Multiple testing activities	Very High	Very High	Broad coverage and flexibility	Higher implementation complexity

BENEFITS OF AI-BASED AUTOMATED TESTING

The integration of AI into AR/VR testing offers several important benefits. First, it reduces repetitive manual testing by allowing intelligent agents to perform large numbers of interactions automatically. Second, AI can increase test coverage by exploring states and interaction sequences that may not be anticipated by human testers. Third, AI can prioritize test cases according to risk, historical failure patterns, or application complexity.

Fourth, computer-vision techniques can automatically inspect visual outputs, which is particularly valuable for immersive applications. Fifth, machine-learning models can support predictive testing by identifying components likely to fail. Sixth, AI can accelerate regression testing because automated agents can repeatedly execute test scenarios after software modifications. A broader review of AI and ML in software testing identifies automated test generation, test execution, result analysis, and failure prediction as important areas in which AI can improve software-testing efficiency. These advantages make AI particularly attractive for large and continuously evolving AR/VR applications.

Despite its potential, AI-based automated testing of AR and VR applications faces significant challenges. One major problem is the enormous state space generated by three-dimensional environments and user interactions. It may be impossible for an AI agent to exhaustively explore all possible states. Another challenge is the lack of standardized datasets and benchmarks for training and evaluating AI-based XR testing systems. AI models may also produce false positives or overlook unusual faults when training data do not adequately represent real-world conditions.

AR testing presents additional reproducibility difficulties because physical environments, lighting, surfaces, device orientation, and user movement can vary between test executions. VR applications similarly require realistic interaction inputs and accurate simulation of human behavior. Hardware diversity creates another challenge because the same application may behave differently across head-mounted displays, controllers, mobile devices, graphics processors, and tracking systems. Finally, AI itself introduces explainability and reliability concerns: a testing system should provide understandable evidence about why a test was selected, why a behavior was considered faulty, and how confident the system is in its conclusion.

FUTURE DIRECTIONS

Future AI-based AR/VR testing is likely to move toward autonomous and multimodal testing systems. Such systems could combine computer vision, reinforcement learning, natural-language reasoning, sensor analysis, and software models to create intelligent virtual testers. Generative AI may further assist in converting requirements into test scenarios, generating diverse interaction sequences, producing synthetic environments, and explaining detected defects.

Another promising direction is continuous testing in which AI agents operate throughout the software development lifecycle and automatically retest applications after code, asset, scene, or configuration changes. Digital twins and simulation environments may allow large-scale testing before deployment on physical XR devices. Hybrid approaches that combine deterministic software testing with AI-based exploration may provide better reliability than relying exclusively on AI. The increasing attention to realistic 3D input generation is particularly important, as recent research indicates that existing VR testing systems still have limitations in automatically synthesizing natural controller-based interactions. Thus, future research should focus on autonomous, explainable, reproducible, cross-platform, and multimodal AI testing frameworks.

II. CONCLUSION

Artificial Intelligence-based automated testing provides a promising approach for addressing the growing complexity of Augmented Reality and Virtual Reality applications. Traditional testing methods remain important but are insufficient to completely address the large state spaces, three-dimensional interactions, visual requirements, environmental dependencies, and hardware diversity associated with immersive applications. AI can improve automated testing through machine learning, deep learning, computer vision, reinforcement learning, intelligent agents, anomaly detection, predictive analytics, and metamorphic testing.

Current research demonstrates that machine-learning-based testing is already an important part of XR testing research, while agent-based and reinforcement-learning approaches provide new possibilities for autonomous exploration and interaction. Nevertheless, limitations involving datasets, computational requirements, reproducibility, explainability, realistic interaction generation, and standardized evaluation remain. Future research should therefore develop integrated AI testing frameworks capable of understanding application behavior, generating realistic user interactions, evaluating visual and functional correctness, detecting performance and usability problems, and continuously learning from testing results. The convergence of AI and XR testing has the potential to transform quality assurance from manually designed test execution toward intelligent, adaptive, and increasingly autonomous software validation.

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